QUANTUM 1/f NOISE IN SOLID STATE DEVICES IN PARTICULAR $Hg_{1-x}Cd_xTe$ N^+-P DIODES

FINAL REPORT

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15 May 1989

U.S. ARMY RESEARCH OFFICE

Proposal number: 22874-EL
Funding document: DAAG-29-85-K-0235

Department of Electrical Engineering
University of Minnesota

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 22874.14-EL
6a. NAME OF PERFORMING ORGANIZATION U of Minnesota 6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS *(City, State, and ZIP Code)* 200 Union St SE Minneapolis, MN 55455	7b. ADDRESS *(City, State, and ZIP Code)* P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-85-K-0235
8c. ADDRESS *(City, State, and ZIP Code)* P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
Quantum 1/f Noise in Solid State Devices in Particular Hg1-xCdxTe N(+)-P (CRH)

12. PERSONAL AUTHOR(S)
A. van der Ziel and A. D. van Rheenen

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final	FROM 9/16/85 TO 3/28/89	15 May 1989	9

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Solid State Devices, Diodes, Quantum Noise, Quantum Theory, and

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The research results are documented in the fourteen reports and publications issued under this contract.

Frequency's incl de i

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)* | 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Papers published under the contract July 1, 1985 to date

A. Early papers on which the present contract is based.

1. A. van der Ziel, C. J. Hsieh, P. H. Handel, C. M. van Vliet, and G. Bosman, "Partition 1/f noise in vacuum pentodes," Physica, vol. 124B, p. 299, 1984.

2. A. van der Ziel and P. H. Handel, "Quantum partition 1/f noise in pentodes," Physica, vol. 125B, p. 286, 1984.
These were the first two papers that indicated the presence of quantum partition 1/f noise in pentodes.

3. A. van der Ziel, P. H. Handel, X. C. Zhu, and K. H. Duh, "A theory of the Hooge parameters of solid-state devices," IEEE Trans. Electron Devices, vol. ED-32, p. 667, 1985.

4. K. H. Duh and A. van der Ziel, "Hooge parameters in various FET structures," IEEE Trans. Electron Devices, vol. ED-32, p. 662, 1985.

5. X. C. Zhu and A. van der Ziel, "The Hooge parameter of n^+-p-n and p^+-n-p silicon bipolar transistors," IEEE Trans. Electron Devices, vol. ED-32, p. 658, 1985.
These were the first papers indicating the possible presence of quantum 1/f noise in FETs and BJTs.

B. Early papers under the contract

6. A. van der Ziel and P. H. Handel, Discussion of a generalized quantum 1/f noise process with applications, Physica, 132B, 367, 1985.
Quantum 1/f noise process described by lumped model.

7. A. van der Ziel, Theory of and experiments on quantum 1/f noise, in Noise in Physical Systems and 1/f Noise, Eds. A. D'Amico and P. Marzztti, Elsevier Science Publishers BV, 11, 1986.
Review paper presented at the Rome Noise Conference, Sept. 1983.

8. X. L. Wu and A. van der Ziel, Experiments on high frequency and 1/f noise in long n^+-p $Hg_{1-x}Cd_xTe$ diodes, in Noise in Physical Systems and 1/f Noise, Eds. A. D'Amico and P. Mazzetti, Elsevier Science Publishers BV, 491, 1986.
Used wrong estimated carrier lifetimes, otherwise correct. First application of the transmission line method.

9. A. van der Ziel and P. H. Handel, "1/f noise in n^+-p diodes," IEEE Trans. Electron Devices, vol. ED-32, p. 1805, 1985.

10. A. van der Ziel and P. H. Handel, "1/f noise in n^+-p junctions calculated with quantum 1/f theory," in Noise in Physical Systems and 1/f Noise, Eds. A. D'Amico and P. Mazzetti, Elsevier Science Publishers BV, p. 481, 1986.
(10) is a better readable version of (9). Discusses recombination-generation and injection-extraction 1/f noise.

11. X. C. Zhu, X. L. Wu, A. van der Ziel and E. G. Kelso, "The Hooge parameters for n-type and p-type $Hg_{1-x}Cd_xTe$," IEEE Trans. Electron Devices, vol. ED-32, p. 1353, 1985.
Tables of the Hooge parameter of $Hg_{1-x}Cd_xTe$ n^+-p diodes versus composition x and temperature T.

C. Papers mentioned in the progress reports

12. P. H. Handel and A. van der Ziel, "Relativistic correction of the Hooge parameter for Umklapp 1/f noise," Physica, vol. 141B, p. 145, 1986.
Relativistic effects become important if $m < 0.02\ m_0$.

13. A. van der Ziel, P. H. Handel, X. L. Wu and J. B. Anderson, "Review of the status of quantum 1/f noise in n^+-p HgCdTe photodiode detectors and other devices," J. Vac. Sci. Technol., vol. A4, no. 4, p. 2205, 1986 (San Diego MCT workshop 1985).
Extensive review of the status of quantum 1/f noise. Still uses wrong estimated values of τ in $Hg_{1-x}Cd_xTe$.

14. A. van der Ziel, "Interpretation of Schwantes's experimental data on secondary emission 1/f noise," Physica, vol. 144B, p. 205, 1987.
Interprets Schwantes' secondary emission 1/f noise as quantum 1/f noise.

15. X. L. Wu, J. B. Anderson and A. van der Ziel, "Diffusion and recombination 1/f noise in long n^+-p $Hg_{1-x}Cd_xTe$ Diodes," IEEE Trans. Electron. Devices, vol. ED-34, p. 602, 1987.
Uses the measured values for τ. Finds from this value $\alpha_H = (3\text{-}5)10^{-3}$ (coherent state) or $\alpha_H = 5\times10^{-5}$ (Umklapp).

16. A. van der Ziel, C. J. Hsieh, P. H. Handel, C. M. Van Vliet and G. Bosman, "Partition 1/f noise in pentodes and its quantum interpretation," Physica, vol. 145B, p. 195, 1987.
Expands and slightly corrects earlier work. Most data agree with the quantum 1/f noise theory, but in one noisy device the quantum 1/f noise seems to be masked by noise of non-quantum origin.

17. P. Fang and A. van der Ziel, "Coherent state quantum 1/f noise in long Si p-i-n diodes at elevated temperatures," in Noise Physical Systems, Ed. C. M. Van Vliet, Montreal, May 1987, World Scientific, Singapore, 410, 1987.
Shows that the devices have coherent state 1/f noise.

18. A. van der Ziel, "Experimental results, possibly involving quantum 1/f noise in devices," in Noise in Physical Systems, Ed. C. M. Van Vliet, Montreal, May 1987, World Scientific, Singapore, 397, 1987.
Gives a survey of quantum 1/f noise experiments.

19. A. van der Ziel, "Semiclassical derivation of quantum 1/f noise in collision-free devices," in Noise in Physical Systems, Ed. C. M. Van Vliet, Montreal, May 1987, World Scientific, Singapore, 427, 1987.
First semiclassical interpretation of quantum 1/f noise in terms of Bremsstrahlung fluctuations.

20. Q. Peng, A. Birbas and A. van der Ziel, "A note for experimental results for the Hooge parameters in P-MOSFETs," in Noise in Physical Systems, Ed. C. M. Van Vliet, Montreal, May 1987, World Scientific, Singapore, 400 (1987).
First semiconductor noise source in which α_H has an L^2 dependence. Later attributed to acceleration 1/f noise.

21. P. Fang and A. van der Ziel, "Study of secondary emission 1/f noise," Physica, 147B, 311 (1987).
Verifies the quantum expression for secondary emission 1/f noise term by term.

22. A. van der Ziel, "Unified presentation of 1/f noise in electronic devices; Fundamental 1/f noise sources," Proc. IEEE, 76, 233 (1988).
First unified presentation of 1/f noise in terms of the Hooge parameter and of fundamental 1/f noise sources. As a side result many quantum 1/f noise formulas are verified experimentally.

23. P. Fang, L. He, Q. Peng, H. Kang, and A. van der Ziel, "1/f noise study in vacuum photodiodes, submitted to J. Applied Physics, 65, 1766 (1989).
Verifies the quantum expressions for photodiode 1/f noise term by term. Shows that the (classical) noise due to work function fluctuations has a $1/f^{3/2}$ spectrum (two-dimensional diffusion over the cathode surface).

24. A. van der Ziel, "The experimental verification of Handel's expression for the Hooge parameter," Solid State Electronics, 31, 1205 (1988).
Based on paper #18, puts chief emphasis on the experimental verification of Handel's expressions.

25. A. van der Ziel, "Semiclassical derivation of Handel's expression for the Hooge parameter, J. Applied Physics, 63, 2456 (1988).
Extension of the derivation of paper (19) to collision dominated devices.

26. A. van der Ziel, "Generalized semiclassical quantum 1/f noise theory; acceleration 1/f noise in semiconductors," J. Applied Physics, 63, 903 (1988).
Extends the theory to the acceleration 1/f noise process and shows that in the latter the Hooge parameter varies as the square of the device length L for intermediate values of L.

27. Q. Peng, A. N. Birbas, A. van der Ziel, A. D. van Rheenen and K. Amberiadis, "Channel-length dependence of the 1/f noise in silicon metal-oxide-semiconductor field-effect transistors, verification of the acceleration 1/f noise process," J. Applied Physics 63, July 1988, 907, (1988)
Shows that the Hooge parameter varies as the square of the device length L for intermediate values of L, as expected from A. van der Ziel's acceleration 1/f noise process. For larger values of L saturation effects are expected.

28. P. Fang, L. He, A. D. van Rheenen, A. van der Ziel and Q. Peng, "Noise and lifetime measurements in Si p^+-i-n diodes," Solid State Electronics, (1989), in press.

29. A. van der Ziel, P. Fang, L. He, X. L. Wu and A. D. van Rheenen, "1/f noise characterization of n_+-p and n-i-p $Hg_{1-x}Cd_xTe$ detectors, J. Vac. Sci Technology, A-7, 550 (1989).

30. A. van der Ziel, Formulation of surface 1/f noise processes in bipolar junction transistors and in p-n diodes in Hooge type form, Solid State Electron, 32, 91 (1989).

D. Papers written during the last eight months of the contract

SECONDARY EMISSION 1/f NOISE REVISITED*

by A. van der Ziel, P. Fang and A. D. van Rheenen

Abstract

Fang and van der Ziel's analysis of secondary emission 1/f noise in secondary emission pentodes is extended to 16 individual data points. It is found that by proper choice of the secondary electron path length d_{da}, good agreement between the experimental values of the Hooge parameter α_H and the theoretical values predicted by Handel's quantum 1/f noise theory is obtained for 14 data points. Handel's equations for the Hooge parameter of the tubes thus seem to have heuristic validity. The values of the secondary electron path length d_{da} differ somewhat from tube to tube and may also depend slightly on bias; these effects are attributed to the electron-optical system formed by screen grid, dynode and anode.

* Accepted for publication in Journal of Applied Physics.

EXTENSIONS OF HANDEL'S 1/f NOISE EQUATIONS AND THEIR SEMICLASSICAL THEORY**

by A. van der Ziel, A. D van Rheenen, and A. N. Birbas

Abstract

By replacing the change in velocity $\Delta\vec{v}$ by the low frequency Fourier transform $\vec{F}(o)$ of the electron acceleration $\vec{a}(t)$, Handel's equations for the Hooge parameter α_H are put in equivalent forms that are not only applicable to collision 1/f noise in semiconductors but also to acceleration 1/f noise in long devices. When the power spectrum $S_p(f)$ of the emitted Bremsstrahlung is evaluated, it contains already the two terms $(q/e)^2$ and $|\vec{F}(o)|^2/c^2$ found in Handel's extended expressions for the Hooge parameter α_H. Going over to elementary events and defining the spectrum of the quantum emission rate $S_q''(f)$ per elementary event by the equation $S_q''(f) = S_p''(f)/[hf\tau_a]$, where τ_a is the duration of the Bremsstrahlung pulse, the expression also contains the factor $4\alpha_0/(3\pi)$ found in Handel's expression for α_H. It thus seems that the Hooge parameter depends only on the Bremsstrahlung emission process but not on the details of the electron-photon interaction. This may explain why Handel's expressions for α_H so often agree with experiment. Introducing the current spectrum $S_I''(f) = S_I(f)/\lambda$ per elementary event where $\lambda = N/\tau_a$ and N the number of carriers, and bearing in mind that $S_I''(f)$ and $S_q''(f)$ come from the same quantum process and are therefore proportional, it is highly likely that the proportionality factor corresponds to the shot noise of an elementary event. This leads immediately to the Hooge equation and to the Hooge parameter α_H.

**Accepted for publication in Physical Review B.

EXTENSION OF THE HOOGE EQUATION AND OF THE HOOGE PARAMETER CONCEPT*

by A. van der Ziel and A. D. van Rheenen

Abstract

The Hooge equation is extended to the case where the noise spectrum is of the form $1/f^{\gamma}$ with γ slightly different from unity. This leads to a generalization of the Hooge parameter that corrects an earlier ambiguity.

* Accepted for publication in Solid-State Electronics.

GENERATION-RECOMBINATION-TYPE 1/f NOISE IN n-i-p DIODES**

by A. van der Ziel, L. He, A. D. van Rheenen, and P. Fang

Abstract

It is shown for p-i-n diodes, in which the current flow is by hole-electron pair generation and (or) recombination, that the $1/f^{\gamma}$ noise is due to generation-recombination processes involving traps and (or) recombination centers and that the spectrum may be written as $S_I(f) = \alpha_H e|I|/[f^{\gamma}\tau]$, where α_H is the Hooge parameter, e the electron charge, $|I|$ the absolute current, τ the time constant associated with the pair generation and pair recombination process, f the frequency and γ is the exponent of the spectrum. This is studied experimentally and the Hooge parameters of various devices are determined.

**Accepted for publication in Solid-State Electronics.

1/f NOISE IN DOUBLE HETEROJUNCTION AlGaAs-GaAs LASER DIODES ON GaAs AND ON Si SUBSTRATES *

by R. Z. Fang, A. C. Young, A. van der Ziel,
A. D. van Rheenen, and J. P. van der Ziel

Abstract

1/f noise measurements at forward bias are reported on double heterojunction AlGaAs-GaAs laser diodes fabricated on GaAs and on Si substrates. The noise spectrum is of the form $1/f^{\beta}$ with β close to unity. $S_I(f)/I$ is roughly independent of current for I < 1mA and decreases with increasing current for I > 1mA. This means that the Hooge equation is valid for I < 1mA with constant α_H/τ, whereas α_H/τ decreases with increasing current for I > 1 mA. Here α_H is the Hooge parameter and τ the carrier lifetime.

The values of α_H/τ for devices on a Si-substrate (#1 and #3) are 20-50 times larger than for devices on a GaAs substrate (#5,6, and 7); this is attributed to the fact that the diodes on a Si-substrate have a much larger dislocation density than the diodes on a GaAs substrate. The current dependence of α_H/τ is a high injection effect. For I << 1mA the carrier density in the active region is equal to the equilibrium density N_0, and $\alpha_H = \alpha_{H0}$ and $\tau = \tau_0 = 2\times10^{-9}$ s are constants; for I >> 1mA there is high injection so that $N \gg N_0$. α_H and τ now decrease with increasing I, and the data require that α_H decreases faster than τ. The diodes with a silicon substrate have $\alpha_{H0} \approx (2.5\text{-}5.0) \times10^{-3}$ for I < 1mA; this value for α_H is probably accidental and does not indicate Hooge type 1/f noise.

* To be submitted to Journal of Applied Physics.